Two-dimensional Helium Plume

1 Introduction

This case provides a description for a two-dimensional helium plume configuration. A mixture fraction is activated that drives mixing and buoyant effects. Although the full physics description can only be represented by a three-dimensional domain, nevertheless, the case captures common instabilities found in buoyant plumes such as Rayleigh/Taylor and Kelvin/Helmholtz phenomena. The baroclinic torque noted in the flow drives the large-scale vortical motion. For more details on the physics of buoyant plumes and fires, see Tieszen's seminal work in fire research [1] and a recent fire validation study of Domino *et al.* [2]. Finally, although the plume enters into the domain as a laminar inflow condition, there exists laminar-to-turbulent transition inspired by the buoyant vertical acceleration. Again, a simplification of this simulation is the under-resolved nature along with an absent turbulence model.

2 Domain

The two-dimensional geometry for this tutorial is captured in Figure 1. Here, pure helium enters a 1 m inflow boundary that is surrounded by a bottom wall plane that is six meters in width and five meters in height. The left and right boundaries are open boundaries where entrainment is expected, while the top is also an open boundary specification where flow leaves the domain. Due to complex vortical flow, the top open boundary experiences periodic entrainment as complex structures exit the domain.

3 Theory

The variable-density low-Mach equation set is defined by the continuity and momentum equation,

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0. \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j} - \frac{\partial \sigma_{ij}}{\partial x_j} = \left(\rho - \rho^o\right) g_i. \tag{2}$$

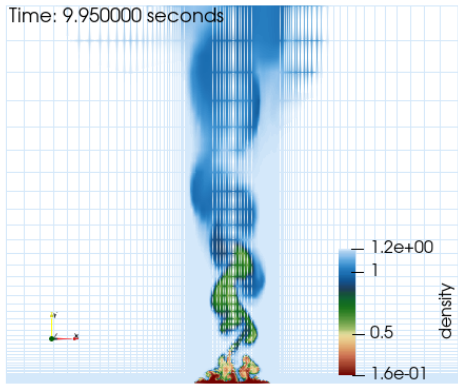


Figure 1: Two-dimensional helium plume configuration. The wire diagram outlines the quadratic Quad9 mesh and density shadings.

In the above equation, ρ is the fluid density and u_j is the fluid velocity. The buoyancy source term is given by the difference between the local density and reference density, ρ^o, scaled by gravity, g_i.

The stress tensor is provided by

$$\sigma_{ij} = 2\mu S^*_{ij} - P\delta_{ij}, \tag{3}$$

where the traceless rate-of-strain tensor is defined as

$$S^*_{ij} = S_{ij} - \frac{1}{3}\delta_{ij}S_{kk} = S_{ij} - \frac{1}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}.$$

In a low-Mach flow, the above pressure, P, is the perturbation about the thermodynamic pressure, P^{th}.

For the buoyant plume configuration of interest, a transport equation for mixture fraction is activated and defined as the mass fraction of species that originates from the inlet boundary condition,

$$\frac{\partial \rho Z}{\partial t} + \frac{\partial \rho u_j Z}{\partial x_j} + \frac{\partial q_j}{\partial x_j} = 0, \tag{4}$$

where the diffusive flux vector is given by $q_j = -\frac{\mu}{Sc}\frac{\partial Z}{\partial x_j}$. Here, the Schmidt number is given as a function of density and mass diffusivity D, as $Sc = \frac{\mu}{\rho D}$. Properties such as viscosity are a linear function of mixture fraction, while density uses inverse weighting.

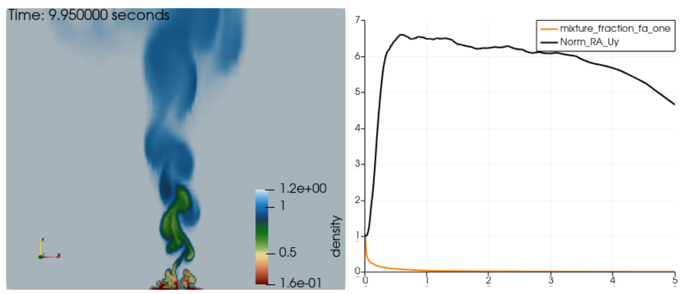
4 Results

This simulation is based on the experimental work of O'Hern [3] where the complex nature of a buoyant plume was studied as a precursor to fire simulations [2].

In this flow, large-scale vortical structure is motivated by the baroclinic torque term (mis-alignment of density and pressure gradients) that drives rotation. Rayleigh/Taylor instabilities (bubble-spike) are captured that drives small-scale mixing.

4.1 Simulation Specification and Results

The simulation activates a Quad9 topology. Inflow of helium (mixture fraction of unity) enters the domain at 0.34 m/s in the y-direction. In Figure 2, the transient density field is provided along with time-mean Reynolds-averaged quantities of interest.



(a)

Figure 2: Density shading (left) and centerline plot of Reynolds-averaged mixture fraction and normalized axial velocity (right).

5 Discussion Points

There are several interesting activities associated with this sample case including the following:

- Ensure that the underlying model suite is well understood.
- Explore the mesh and input file specifications associated with this case.
- Please comment on the form of the buoyancy source term and how this drives the pressure specification in the input file.
- Note the puffing structure and Rayleigh/Taylor instability.
- What is a good time-averaging interval to use in this simulation. Note that correlation-based approaches for the temporal puffing frequency is roughly $\frac{1.5}{\sqrt{(d_o)}}$.
- Please comment on the issues with running a two-dimensional configuration for this physics-set. What about the lack of a turbulence model activated in the configuration?

References

[1] Tieszen, S., *On the fluids mechanics of fires*, Annual Review of Fluid Mechanics, Vol. 33, 2001.

[2] Domino, S. P., Hewson, J., Knaus, R., Hansen, M., *Predicting large-scale pool fire dynamics using an unsteady flamelet- and large-eddy simulation-based model suite*, Physics of Fluids, Vol. 33, 2021.

[3] O'Hern, T., Weckman, E., Gerhart, A., Tiezen, S., Sheffer, R., *"Experimental study of a turbulent buoyant helium plume*, Journal of Fluid Mechanics, Vol. 544, 2005.